IN THE DRAWING

Please replace FIGs 1 and 4 with the enclosed replacement FIGs 1 and 4.

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REMARKS

This Amendment is being filed in response to the Office Action mailed August 22, 2006, which has been reviewed and carefully considered. Reconsideration and allowance of the present application in view of the amendments made above and the remarks to follow are respectfully requested.

At the outset, it is respectfully pointed out that, on page 1 of the Office Action, box 3 is incorrectly checked indicating that "this application is in condition for allowance except for formal matters, prosecution as to the merits is closed." It is believed that box 3 is incorrectly checked in view of the various formal rejections included in the body of the Office Action. Commensurately, the time period to reply to the Office Action noted on the first page as being 2 months is also believed to be in error (and should have been 3 months). Nevertheless, the present Amendment is being filed within the 2-month period noted on page 1 of the Office Action.

In the Office Action, it is indicated that the information disclosure statement (IDS) mailed on January 19, 2006, listed an

article by M. Steinbuch, "Repetitive Control for Systems with Uncertain Period-Time," Automatica In Press 09/04/2002, pp 1-7. However, the Examiner alleged that a copy of this article was not included with the IDS, and required a copy. Applicant greatfully thanks the Examiner for pointing out that the article was not received, a copy of which is enclosed.

By means of the present amendment, the specification has been amended for better clarity.

In the Office Action, the Examiner noted that FIG 1 should be labeled "Prior Art". In response, FIGs 1 and 4 have been amended in accordance with the Examiner's suggestion and for conformance with the specification such as page 2, lines 18 and 23-25. Applicant respectfully requests approval of the enclosed proposed drawing changes.

In the Office Action, the Examiner reminded the Applicant of the proper language and format for the Abstract. In response, the current Abstract has been deleted and substituted with the enclosed New Abstract which better conforms to U.S. practice.

In the Office Action, claims 1-2 are rejected under 35 U.S.C. §112, second paragraph as allegedly indefinite. Without agreeing

with the Examiner, and in the interest of advancing prosecution, claims 1-2 have been amended to remove the informality noted by the Examiner. It is respectfully submitted that the rejection of claims 1-2 has been overcome and an indication as such is respectfully requested.

In the Office Action, claims 1-2 are rejected under 35 U.S.C. §112, first paragraph as allegedly failing to comply with the enablement requirement. It is respectfully submitted that the specification and drawings provide ample support and sufficient description, as well as fully enable claims 1-2, in such a way as to reasonably convey to one skilled in the relevant art how to make and/or use the present invention without any undue experimentation.

It is respectfully submitted that it would be a trivial matter for a person skilled in the art to make and/or use the claimed invention defined by the claims 1-2, where one embodiment is shown in FIG 2. Clearly one skilled in the art would have no trouble implementing the diagram shown in FIG 2, where a FIFO memory buffer with N/2 taps is fed by, or receives, a signal having a period of NT, N being an integer and T being a time period. The output of the buffer is fed back to its input though a subtractor, thus

providing negative feedback. The output of the buffer is also multiplied by a scalar, such as -1/2. As described on page 3, lines 2-4, the scalar (-1/2) is included at the output of the loop shown in FIG 2 in order to adjust the gain and phase of the output signal, so that the proposed loop of FIG 2 matches the gain and phase of a classical memory loop shown in FIG 1.

Clearly, the specification including the figures comply with the written description and enablement requirement, and reasonably convey that the inventor, at the time of the application was filed had possession of the claimed invention, as well as reasonably convey to one skilled in the relevant art how to make and/or use the present invention without any undue experimentation. Accordingly, withdrawal of this rejection under 35 U.S.C. §112, first paragraph is respectfully requested, and allowance of claims 12-18 is respectfully requested.

In the Office Action, claim 1 is rejected under 35 U.S.C. §103(a) as allegedly unpatentable over U.S. Patent No. 5,740,090 (Steinbuch). Claim 2 is rejected under 35 U.S.C. §103(a) as allegedly unpatentable over U.S. Patent No. 6,765,848 (Faucett) in view of Steinbuch. It is respectfully submitted that claims 1-2

are patentable over Steinbuch and Faucett for at least the following reasons.

Steinbuch is directed to a repetitive control system with filters composed of delay circuits and having parameters resulting in a very high loop gain for only specific frequencies.

It is respectfully submitted that Steinbuch does not teach or suggest the present invention as recited in independent claims 1-2, where amongst other patentable elements, require (illustrative emphasis provided):

> a memory loop fed with a periodic signal of period NT and in which the memory size includes N/2 memory elements, the feedback connection is negative and a factor of -½ is provided at the output of the memory loop, wherein N is an integer and T is period of time.

These features are nowhere taught or suggested in Steinbuch. Faucett is cited to allegedly show other features and does not remedy the deficiencies of Steinbuch. Accordingly, it is respectfully submitted that independent claims 1-2 are allowable, and allowance thereof is respectfully requested.

In addition, Applicants deny any statement, position or averment of the Examiner that is not specifically addressed by the

foregoing argument and response. Any rejections and/or points of argument not addressed would appear to be moot in view of the presented remarks. However, the Applicants reserve the right to submit further arguments in support of the above stated position, should that become necessary. No arguments are waived and none of the Examiner's statements are conceded.

It is believed that no additional fees or charges are currently due. However, in the event that any additional fees or charges are required for entrance of the accompanying amendment, they may be charged to Applicants' representatives Deposit Account No. 50-3649. In addition, please credit any overpayments related to any fees paid in connection with the accompanying amendment to Deposit Account No. 50-3649.

In view of the above, it is respectfully submitted that the present application is in condition for allowance, and a Notice of Allowance is earnestly solicited.

Respectfully submitted,

By_______________
Dicran Halajian, Reg. 39,703
Attorney for Applicant(s)
October 23, 2006

Enclosure: Replacement drawing sheets (2 sheet2 including FIGs 1 and 4)
New Abstract
Steinbuch Article entitled "Repetitive Control for Systems with Uncertain Period-Time" (7 pages)

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Brief Paper

Repetitive control for systems with uncertain period-time ☆

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Received 20 December 1999; received in revised form 5 February 2002; accepted 14 June 2002

Abstract

Repetitive control is useful if periodic disturbances act on a control system. Perfect (asymptotic) disturbance rejection is achieved if the period-time is exactly known. For those cases where the period-time changes and cannot be measured directly by an auxiliary signal, a robust repetitive controller structure is proposed. It uses multiple memory-loops in a certain feedback configuration, such that small changes in period-time do not diminish the disturbance rejection properties. The robust repetitive controller shows good implementation results for a tracking control problem of a Compact Disc player.

Keywords: Repetitive control; Compact disc player; Periodic disturbances; Internal model principle

1. Introduction

Control systems subject to periodic disturbances may well benefit from the use of *repetitive control*. Repetitive controllers employ the internal model principle and consist of a periodic signal generator, enabling perfect (asymptotic) rejection of periodic disturbances. In case of tracking systems where the task (setpoint) is known to be a predetermined (repeatedly supplied) trajectory, repetitive control is used in a semi-open-loop (feedforward) fashion known as *iterative learning control*. In cases where periodic measurement noise is significant, repetitive control is applied in the form of digital comb-filters for noise reduction. Tomizuka, Tsao, and Chew (1988), Hara, Yamamoto, Omata, and Nakano (1988), Chew and Tomizuka (1990), Hillerström (1996), Moore, Dahley, and Bhattacharyya (1992), Yamamoto (1993), Bodson, Sacks, and Khosla (1994), Messner and Bodson (1994) and de Roover, Bosgra, and Steinbuch (2000) cover most of the relevant developments in repetitive and learning control.

A block-diagram of a closed-loop system including a repetitive controller as add-on device, is shown in Fig. 1.

Here the reference signal r, or any disturbance acting on the system, is assumed to be a periodic signal with known and fixed period-time. The additional device, denoted as 'memory-loop' is a delay line with length equal to the period-time of the external signals and with a positive feedback. This constitutes a periodic signal generator. In Section 2 this standard repetitive control configuration will be explained further.

One of the drawbacks of repetitive control is the requirement of exact knowledge of the period-time of the external signals. This means that in practical applications, either the period-time is required to be constant (±0.1%), or an accurate measurement of the periodicity is necessary. In literature several solutions have been proposed, most of them considering a supervisory adaptive scheme to estimate the period-time from closed-loop on-line measurements, see for instance Tsao and Nemani (1992), Dötch, Smakman, Van den Hof, and Steinbuch (1995), and Manayathara, Tsao, Bentsman, and Ross (1996). In contrast to the literature, in this paper we will propose a new structure for repetitive control which is *robust* for changes in period-time (Section 3). The robust repetitive controller will be experimentally tested for the servo control of a Compact Disc player (Section 4). Finally, in Section 5 we will summarize the main contributions in the concluding remarks.

☆ This paper was not presented at any IFAC meeting. This paper was recommended for publication in revised form by the Associate Editor Shinji Hara under the direction of Editor Roberto Tempo.

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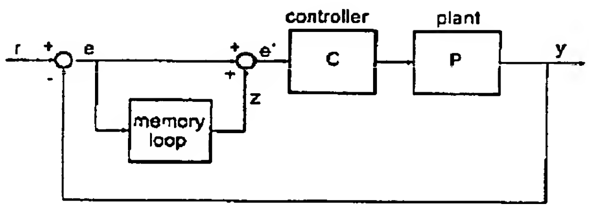

Fig. 1. Block diagram of a control loop including a repetitive controller.

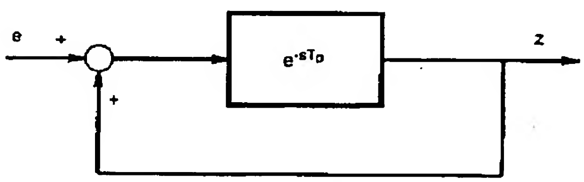

Fig. 2. Block diagram of a standard memory-loop.

2. Repetitive control

2.1. Periodic signal generator

The internal model principle (Francis & Wonham, 1975) states that for asymptotically tracking a reference command by the output of a closed-loop system, a realization (model) of the disturbance/reference generating system should be included in the feedback loop. As a well-known example, signals with a DC ($\omega = 0$) content can be modelled using an integrator, and inclusion of integral action in the feedback controller prevents steady-state errors for constant references and disturbances. A discrete time integrator is a positive feedback over one delay, implying that one memory location is used to store the integral value. With zero input the integral value updates itself by the positive feedback loop.

Similarly, for *periodic* signals, a memory loop can be used which generates an output at frequencies $k\omega_p$, with k integer and ω_p the period frequency. In a memory loop, a signal with period $T_p = 2\pi/\omega_p$ is stored in a FIFO buffer. Depending on T_p and the sample frequency a number of memory locations is needed. If a positive feedback is put over this FIFO buffer, in steady state no input is needed to generate an output with period time T_p. Such a periodic signal has a discrete frequency spectrum with peaks at $\omega = k\omega_p$. A block diagram of a memory-loop with period time T_p is shown in Fig. 2.

Although the common implementation of memory-loops is done in discrete time, in this paper we will adopt a description in continuous time in order to derive some insightful results. Note that a time delay is equal to e^{-sT_p}. The transfer function from e to z is (see Fig. 2)

$$\frac{z}{e} = G(s) = \frac{e^{-sT_p}}{1 - e^{-sT_p}}. \tag{1}$$

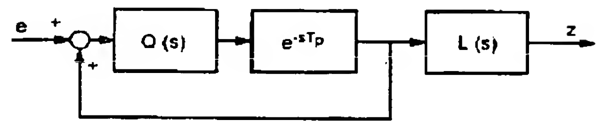

Fig. 3. Block diagram of the implemented memory-loop.

For frequencies $\omega = k\omega_p = k2\pi/T_p$ the magnitude of the denominator of $G(s)$ is zero, making the gain of the transfer function infinite. This, of course, is the intended working principle of the repetitive controller: to have infinite loop gain at the harmonics of the disturbance. However, such gains may easily cause stability problems in the main (outer) servo loop. Stability of repetitive controllers has been thoroughly analyzed by Tomizuka et al. (1988), Chew and Tomizuka (1990) and Hillerström (1996). To guarantee stability two filters $Q(s)$ and $L(s)$ are added to the repetitive signal generator as shown in Fig. 3.

The filter $L(s)$ usually is called the learning filter, and it is used to compensate the transfer as seen by the repetitive controller. The filter $Q(s)$ is used to reflect the mismatch between $L(s)$ and the real system; it limits the working of the repetitive controller to a certain frequency band. It is beneficial to construct $Q(s)$ such that its phase behavior is linear with frequency. In that case we can compensate the phase delay introduced by $Q(s)$ by adjusting the delay of the periodic signal generator. It is not the purpose of this paper to investigate the design of the filters $L(s)$ and $Q(s)$. Instead we refer to the literature (Tomizuka et al., 1988; Hillerström, 1996).

2.2. Sensitivity analysis

Let us return to the basic building block of a repetitive controller, see Fig. 2. A frequency response of this filter $G(s)$ is shown in Fig. 4 for the first few harmonics (13 in this case; $T_p = 1/7.5$ s). Clearly, at the harmonic frequencies the gain is infinite as predicted from Eq. (1).

However, the additional gain is only obtained in a very limited frequency band centered around each harmonic. In some applications the period time is not exactly known or cannot be measured accurately enough. To further analyze the sensitivity of the repetitive controller for changes in the period-time, consider Eq. (1) if the period time is perturbed with a multiplicative error α: $T_p(1+\alpha)$.

The transfer function $G_p(s)$ for the perturbed periodic signal generator then becomes

$$\frac{z}{e} = G_p(s) = \frac{e^{-sT_p(1+\alpha)}}{1 - e^{-sT_p(1+\alpha)}} \tag{2}$$

and at the harmonics we obtain with $s = jk2\pi/T_p$:

$$\frac{z}{e} = \frac{e^{-jk2\pi(1+\alpha)}}{1 - e^{-jk2\pi(1+\alpha)}}. \tag{3}$$

In Fig. 5 the magnitude of Eq. (3), for the first harmonic ($k = 1$), is plotted as a function of the perturbation α: solid

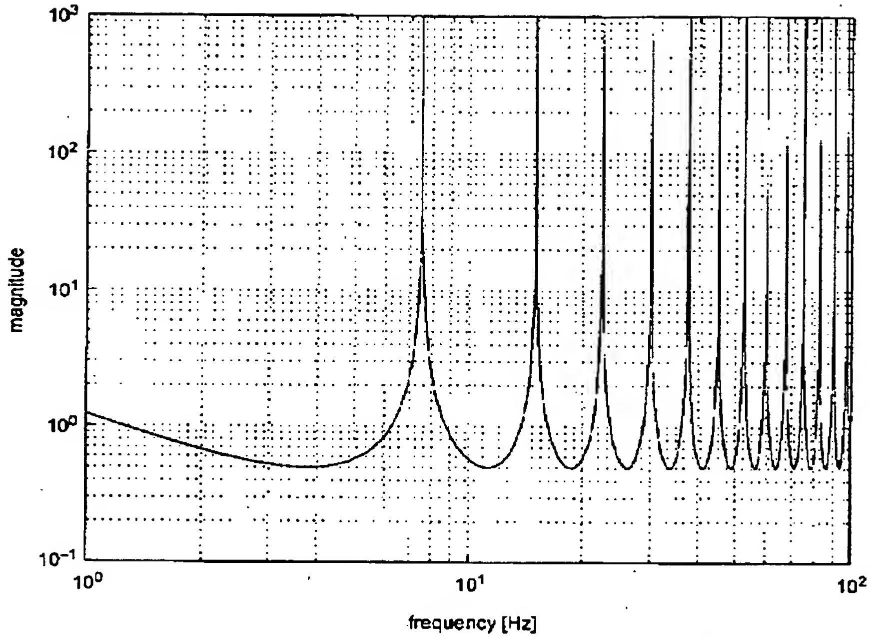

Fig. 4. Magnitude frequency response $G(j\omega)$ of a periodic signal generator.

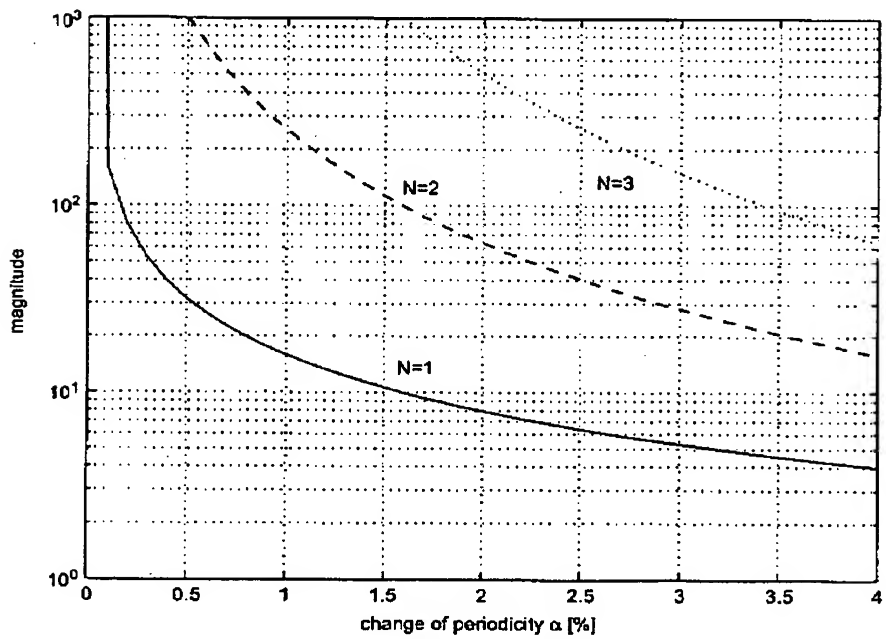

Fig. 5. Magnitude of a periodic signal generator as function of the period-mismatch, evaluated for the first harmonic ($k = 1$), for the standard repetitive controller ($N = 1$), and for robust repetitive controllers ($N = 2$ and $N = 3$).

line (with label $N = 1$; the variable N will be introduced in the next section). As can be seen, already for a perturbation of 1.5% ($\alpha = 0.015$) the gain drops from ∞ to 10. For higher harmonics (not shown in the figure) this is even more pronounced: for example for the tenth harmonic ($k = 10$), the gain is only 1.1.

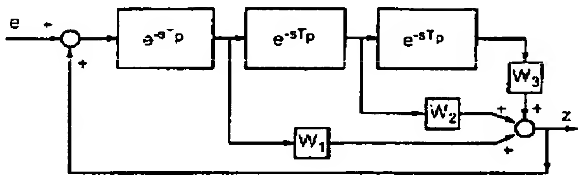

Fig. 6. Generalized repetitive controller.

In the next section we will present an extended repetitive controller to improve the robustness for uncertainties in the period-time.

3. Robust repetitive control

Consider a generalized repetitive controller, consisting of multiple periodic signal generators in a structure as shown in Fig. 6 for an example with three elements.

In Gotou, Ueta, Nakamura, and Matsuo (1991) also multiple memory loops are used, but here the weighting factors are used to modify the dynamic response in between the harmonic frequencies.

The transfer function of a generalized repetitive controller with N periodic signal generators can be written as

$$\frac{z}{e} = G(s) = \frac{H(s)}{1 - H(s)} \tag{4}$$

with the loop transfer function $H(s)$:

$$H(s) = \sum_{i=1}^{N} W_i e^{-isT_p}. \tag{5}$$

Again, we would like the periodic signal generator $G(s)$ to become infinite at the harmonics, i.e. $H(s) = 1$ for $s = jk2\pi/T_p$. Substitution of these values of s into Eq. (5) gives

$$H(jk2\pi/T_p) = \sum_{i=1}^{N} W_i e^{-ijk2\pi} = \sum_{i=1}^{N} W_i = 1. \tag{6}$$

Indeed for $N = 1$, we find $W_1 = 1$ which gives the standard repetitive controller from the previous section. In order to improve the robustness of the repetitive controller for variations of the period-time, we also impose the requirement

$$\frac{\partial H(s = jk2\pi/T_p)}{\partial T_p} = 0 \tag{7}$$

which gives

$$\frac{\partial H(s)}{\partial T_p} = \frac{\partial \sum_{i=1}^{N} W_i e^{-isT_p}}{\partial T_p} = \sum_{i=1}^{N} - W_i i s e^{-isT_p} \tag{8}$$

and for $s = jk2\pi/T_p$ we find

$$\frac{\partial H(jk2\pi/T_p)}{\partial T_p} = \sum_{i=1}^{N} - W_i i j k 2\pi/T_p = 0 \tag{9}$$

hence, for the case with $N > 1$,

$$\sum_{i=1}^{N} W_i i = 0 \tag{10}$$

will meet the requirement.

Since we have a structure with N delay lines, and N parameters W_i, we can impose N constraints. To further decrease the sensitivity for period-time variations, we can impose upto $(N-1)$th derivatives equal to zero:

$$\sum_{i=1}^{N} W_i i^{(N-1)} = 0. \tag{11}$$

In Fig. 7 the magnitude frequency responses are plotted for a repetitive controller with one, two and three memory loops, respectively. Clearly, for a wider frequency band around the harmonics the gain is higher, which leads to a smaller sensitivity for period-time changes. This can also be observed in the sensitivity plot Fig. 5 ($N = 2, 3$).

As an example consider the case with two memory loops ($N = 2$). Then we find from Eqs. (6) and (10) $W_1 + W_2 = 1$ and $W_1 + 2W_2 = 0$, hence $W_1 = 2$, $W_2 = -1$ is the solution pair. By induction we can state that the proposed robust repetitive controller with N weights is given by

$$\frac{z}{e} = \frac{1 - (1 - e^{-sT_p})^N}{(1 - e^{-sT_p})^N}. \tag{12}$$

It should be noted that an equivalent principle occurs in the time domain for robustifying the so-called *input shapers*, see Singer (1993) and Singh and Vadali (1993). The robust repetitive controller proposed here has been successfully patented (Steinbuch & Schootstra, 1998); an adaptive version has been developed for handling larger variations of the period-time. This adaptive version is based on correlation analysis of stored information in the FIFO buffer, see Schootstra and Steinbuch (1998). In the next section we will show experimental results for the tracking problem of a Compact Disc mechanism.

4. Application to a compact disc drive

4.1. Standard repetitive control

In Fig. 8 a schematic view of a Compact Disc mechanism is shown. The mechanism is composed of a turn-table DC-motor for the rotation of the Compact Disc, and a radial arm for the track-following. An objective lens, suspended by two parallel leaf springs, can move in a vertical direction to give a focusing action.

In Fig. 9 a block-diagram of the radial (tracking) control loop is shown. The difference between the radial track position and the spot position is detected by the optical pick-up; it generates a radial error signal (RE) (Steinbuch, van Groos, Schootstra, Wortelboer, & Bosgra, 1998). In current systems the servo controller is a PID controller

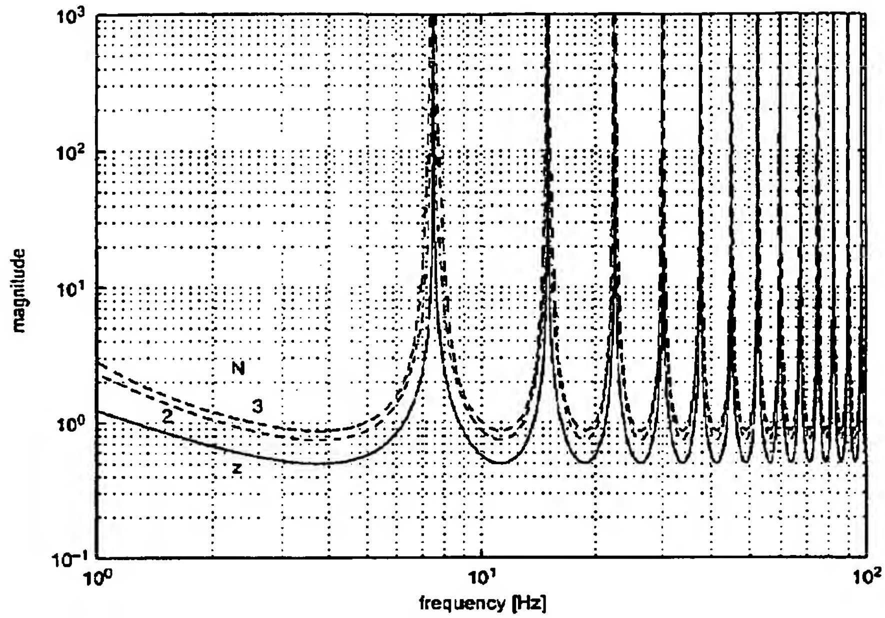

Fig. 7. Magnitude frequency responses $G(j\omega)$ of multiple periodic signal generators.

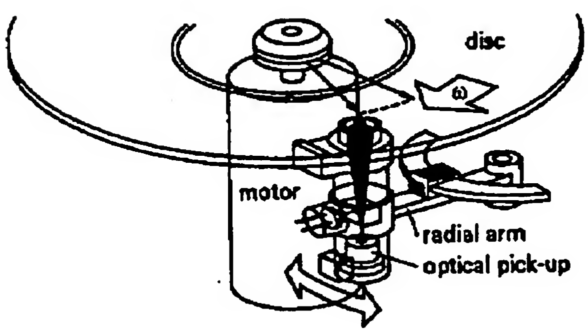

Fig. 8. Schematic view of a rotating arm Compact Disc mechanism.

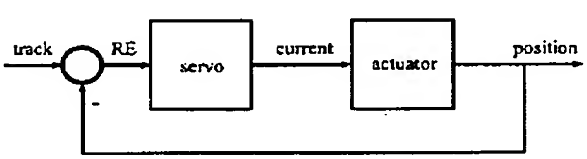

Fig. 9. Configuration of the Compact Disc tracking control loop.

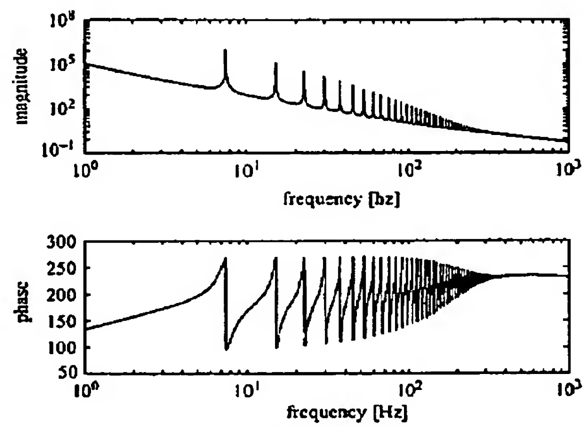

Fig. 10. Open-loop frequency response of a memory-loop in series with a PID controller and a double integrator.

(Steinbuch & Norg, 1998). The tracking control loop has a cross-over frequency of 500 Hz.

Fig. 10 shows the open-loop frequency response of the Compact Disc control system model, in this case a series connection of a double integrator as plant (mass to be positioned), a lead filter with integral action (PID controller (Steinbuch & Norg, 1998)) and the repetitive controller (with low-pass digital FIR filters $Q(z)$ and $L(z)$, cut-off at 150 Hz, with linear phase characteristics). Using frequency response analysis, stability of the controlled system can be checked, using standard Nyquist arguments. Note that the phase change at the harmonic frequencies is from 270 back to 90° and thus compensates for the phase change between the harmonics.

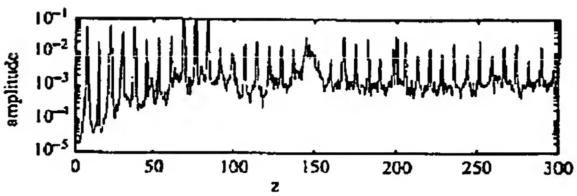

Fig. 11. Amplitude spectrum of radial error (RE) using a standard servo loop.

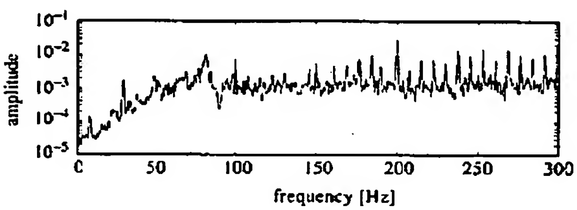

Fig. 12. Amplitude spectrum of RE when a memory-loop is added.

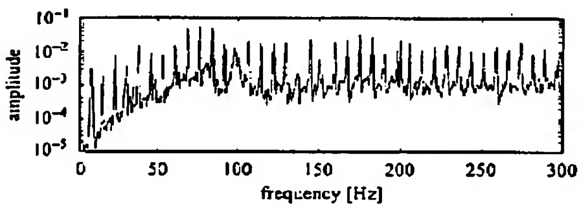

Fig. 13. Spectrum of RE using a standard memory-loop perturbed by 0.5%.

A measured amplitude spectrum of the radial servo error (RE) is shown in Fig. 11 for the PID controlled tracking servo. The periodic contents of the tracking error is clearly visible in a large number of harmonics of the rotational frequency ($\omega_p = 2\pi 7.5$ rad/s) of the disc.

If a memory-loop is correctly tuned and locked to the disturbance period, error reductions can be very large. As an example the amplitude spectrum of the resulting radial tracking error is shown in Fig. 12. Up to a frequency of 150 Hz (20 harmonics) the periodic components are suppressed. This clearly shows the remarkable improvements possible with repetitive control. However, as mentioned before, the improvements are very sensitive for variations of the period-time. To show this, we changed the frequency of the disc by only 0.5%, while keeping the same repetitive controller. The resulting amplitude spectrum of the radial tracking error is shown in Fig. 13.

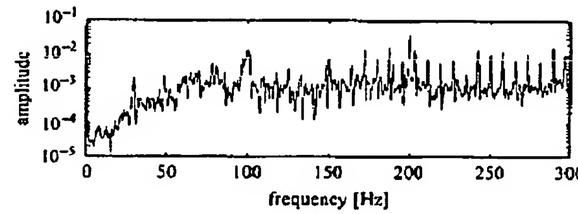

Fig. 14. Spectrum of RE using a robust ($N = 2$) memory-loop perturbed by 0.5%.

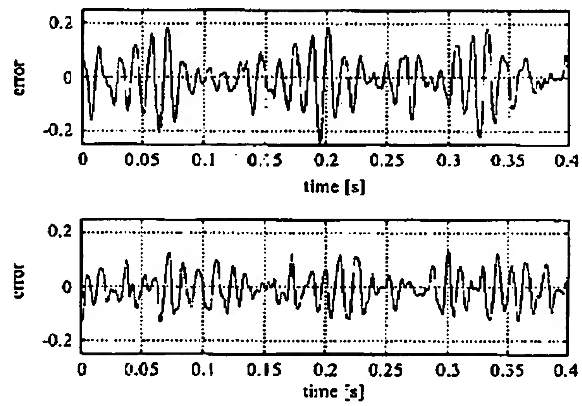

Fig. 15. Remaining error signals of a standard (top) and a robust memory-loop (bottom) when the period-time is perturbed by 0.5%.

4.2. Implementation results with robust repetitive control

In order to evaluate the robust memory-loop in reality, an implementation has been done for the case $N = 2$. The amplitude spectrum of the tracking error is shown in Fig. 14 for the robust ($N = 2$) repetitive controller with a 0.5% change in disc rotational frequency. Compare this with the spectrum plot in Fig. 13 for the standard ($N = 1$) repetitive controller. It is clear that the robust memory-loop has a much better reduction compared to the $N = 1$ case. The improvement can be predicted also for other perturbation levels, by the use of Fig. 5.

Finally, the error signals in the time-domain are shown in Fig. 15 (the time-domain signals are low-pass filtered at 125 Hz in order to show the difference more clearly).

The robustification of the memory-loop as explained above, of course, has the disadvantage of the need of more storage capacity. This increases with the length NT_p of the FIFO.

5. Conclusions

The use of memory-loops is beneficial in systems with repetitive disturbances or tasks. In order to improve the ca-

pabilities of repetitive controllers for those cases where the periodicity is hard to measure and is subject to variation, an extension of repetitive control is developed. By using multiple memory-loops, and correct design of the coefficients, significant robustness is achieved for small variations in the period time. The robust repetitive controller has been implemented successfully in a digital control setup of a Compact Disc player. Future research will be focused on possible application of the same idea to the so-called 'high-order' iterative learning control.

Acknowledgements

The author would like to thank Gerrit Schootstra for his participation in the project, and Tarunraj Singh, University of Buffalo, for helpful suggestions and corrections, especially for pointing out Eq. (12).

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